INSTITUTE OF PHYSICS PUBLISHING PLASMA PHYSICS AND CONTROLLED FUSION

Plasma Phys. Control. Fusion **47** (2005) 1101–1108 doi:10.1088/0741-3335/47/7/009

Bright spots generated by lower hybrid waves on JET

K M Rantamäki[1], V Petržílka[2], P Andrew[3], I Coffey[4], A Ekedahl[5], K Erents[3], V Fuchs[2], M Goniche[5], G Granucci[6], E Joffrin[5], S J Karttunen[1], P Lomas[3], J Mailloux[3], M Mantsinen[7], M-L Mayoral[3], D C McDonald[3], J-M Noterdaeme[8,9], V Parail[3], A A Tuccillo[10], F Žáček[2] and Contributors to the EFDA—JET Workprogramme

[1] Association Euratom—Tekes, VTT Processes, P O Box 1608, FIN-02044 VTT, Finland
[2] Association Euratom—IPP. CZ, Za Slovankou 3, 182 21 Prague 8, Czech Republic
[3] Association Euratom—UKAEA, Culham Science Centre, Abingdon, OX14 3DB, UK
[4] Queen's University, Belfast, BT7 1NN, UK
[5] Association Euratom—CEA, CEA/Cadarache, F-13108 St. Paul-lez-Durance, France
[6] Association Euratom—ENEA sulla Fusione, IFP-CNR, Via R Cozzi, 53-20125 Milano, Italy
[7] Association Euratom—Tekes, Helsinki University of Technology, FIN-02015 HUT, Finland
[8] Association Euratom—Max-Planck IPP, D-85748 Garching, Germany
[9] Gent University, EESA Department, Belgium
[10] Association EURATOM-ENEA, CR ENEA Frascati, C.P. 65, 00044 Frascati, Rome, Italy

Received 23 September 2004, in final form 4 March 2005
Published 20 June 2005

Abstract

Observations of bright spots on the JET divertor aprons during lower hybrid current drive experiments are described. These bright spots are important because they can potentially cause damage to large tokamaks. The bright spots arise due to the impact of a fast particle beam. This beam originates from the front of the lower hybrid launcher, where thermal particles are accelerated according to theory by interaction with the high spatial harmonics of the lower hybrid wave. The bright spots are clearly related to the lower hybrid power as they disappear when the lower hybrid power is switched off. According to the analysis versus various parameters, the brightness of the spots clearly decreases with increasing plasma–wall distance, i.e. the distance between the last closed flux surface and the poloidal limiter. This is clearly beneficial for ITER, as it is designed to operate at a large plasma–wall distance.

1. Introduction

Efficient coupling of lower hybrid (LH) power from the wave launcher (grill) to the plasma is a very important issue in LH current drive (CD) experiments. Recent experiments [1] have demonstrated successful coupling in reactor relevant conditions. The antenna–plasma distance was up to 10.5 cm and the coupling remained good even in the presence of ELM activity.

0741-3335/05/071101+08$30.00

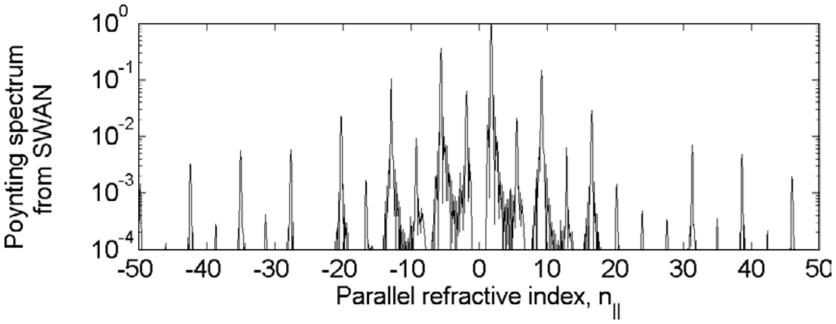

Figure 1. Power spectrum of the JET LH launcher at the grill mouth calculated by SWAN for an edge density of $n_e = 3 \times 10^{18}\,\mathrm{m}^{-3}$.

However, the formation of hot (bright) spots on components magnetically connected to the grill region remains a concern. In recent LHCD experiments at JET, bright spots have been observed in the divertor region [2]. The most probable reason is the fast electron generation by parasitic absorption of LH power in front of the grill mouth, as observed in LHCD experiments on Tore Supra and TdeV tokamaks [3, 4]. Here by parasitic absorption, we mean the absorption of the very high $n_{||}$ modes of the spectrum with $n_{||} > 20$, which was first predicted by test particle calculations [5] and later confirmed by self-consistent particle-in-cell simulations [6]. Figure 1 shows a typical power spectrum, normalized to the maximum value, for the JET LH grill as calculated by the SWAN coupling code [7]. The power content in the modes with $|n_{||}| > 20$ is about 3%. The high-$n_{||}$ modes have low enough phase velocity to interact with the cold edge electrons. At high power levels these modes have overlapping trapping widths in velocity space and the electron acceleration becomes stochastic [5]. PIC simulations performed for both JET and Tore Supra are presented in [8], which shows that the results for the two devices are similar. On Tore Supra, the parallel heat fluxes on the grill limiters were typically 5–10 MW m^{-2} but in extreme cases up to 30 MW m^{-2} was measured [3].

In recent JET experiments described in the present paper, series of bright spots have been detected on the inner and outer divertor apron, which are magnetically connected to the LH grill region. The LH power in these experiments was between $P_{\mathrm{LH}} = 1$ and 3 MW and strong gas injection near the grill was used to improve the coupling. Gas puffing was needed because the LH waves can only propagate in a plasma with a density above the cut-off density. In some cases, however, excess of gas in front of the grill may increase the heat flux to the magnetically connected components.

The JET LH launcher is powered by a 12 MW generator at 3.7 GHz, and it is composed of twelve rows of 32 narrow waveguides in the toroidal direction. Built-in phase shifters result in a 90° phasing between adjacent waveguides. This waveguide arrangement allows us to launch a wave spectrum with a large part of the wave energy in the wave mode with the parallel index centred at $n_{||} = 1.8$, which is suitable for current drive. However, a fraction of the wave energy is also radiated by modes with higher $n_{||}$, which may efficiently be absorbed even by thermal particles in front of the grill mouth. In turn, these cold ($T_e \sim 25$ eV) particles in front of the grill mouth may be accelerated by the LH waves upto energies in the several keV range.

In this paper, we present results from recent experiments on the formation of bright spots on the JET divertor aprons. The spots were observed during high power LH current drive experiments in which the tail of the pulses was designed to enable the study of the spots. An analysis of the brightness versus various parameters will be presented.

Table 1. Parameters of the shots described in this report at the times the shots show bright spots.

Shot number	Plasma current, I_p (MA)	Toroidal field, B_T (T)	LH power, P_{LH} (MW)	Safety factor, q_{95}	Gas	Gas rate (10^{21} el s^{-1})	Grill position, L_{pos} (cm)	Plasma-grill distance (cm)
55761	−3.1	−3.44	2.0	3.5–3.3	CD_4	8.0	−1.5	5.5
55761	−3.5	−3.44	2.5	3.1	CD_4	8.0	−1.5	5.5
55763	−3.1	−3.44	1.5	3.5–3.3	CD_4	6.5	−1.5	5.5
55764	−2.5	−3.44	2.4	4.5–4.2	CD_4	8.5	−1.5	5.5
55764	−3.1	−3.44	2.0	3.5–3.3	CD_4	8.5	−1.5	5.5
58386	−3.2	−3.20	1.5	3.6–3.4	CD_4	7.0	−1.0	6.5
58387	−3.1	−3.20	1.0	3.7–3.4	CD_4	7.0	−1.0	6.5
58388	−3.2	−3.20	1.6	3.6–3.4	CD_4	7.0	−1.0	6.5
58666	−2.1	−3.00	2.5	5.1–4.5	D_2	8.0	−1.5	6.5
58666	−2.4	−3.00	2.5	4.1–3.8	D_2	8.0	−1.5	6.5
58667	−2.1	−3.00	2.5	5.1–4.5	D_2	8.0	−2.0	10.5
58667	−2.4	−3.00	2.5	4.1–3.8	D_2	8.0	−2.0	10.5
58668	−2.1	−3.00	3.0	5.1–4.5	D_2	8.0	−1.5	6.5
58668	−2.5	−3.00	3.0	4.1–3.8	D_2	8.0	−1.5	6.5

2. Experimental set-up

In order to observe the bright spots on the divertor apron with good spatial resolution, a CCD camera [9] was used. The spots are apparently formed in most shots with LH power. However, due to the fixed line of sight of the CCD camera and the fact that the magnetic field lines do not always end up on the apron in this area, the spots are not always seen. The connection point of the magnetic field lines on the apron depends on the safety factor $q = rB_T/(R_0B_p)$, where r is the minor radius of the flux surface, R_0 is the major radius, and B_T and B_p are the toroidal and poloidal fields, respectively. The q_{95}-value (q at 95% of flux) is an important parameter as it defines the field line connection from the grill mouth to the divertor region. Consequently, the best possibility to detect the spots with the CCD camera is in the current ramp up or down phase, in which the q_{95}-value changes.

In this work, three sets of shots with observed hot spots were analysed. In all the shots, a current ramp-up was used to increase the possibility of having the connection points visible to the CCD camera, i.e. to have suitable q_{95}-values. In the first two sets, the ramp-up phase lasted for the whole shot while in the last set the current was ramped up only at the end of the pulse. In the first part of the shots of this last set, the q_{95} was above 7, which is much higher than the values (4.3, 3.4 or 3.1) at which hot spots had been observed in earlier experiments. The current ramp-up then brought the q_{95}-values down to the level at which the hot spots could be seen by the CCD camera. In some cases, the ramping rate was decreased in order to prevent disruptions by MHD activities. Because of this limitation it was not possible to push the q_{95}-value down to 3.1.

The magnetic field varied between $B = 3$ and 3.5 T from shot to shot. The grill position was 1–2 cm behind the limiter and the distance from the limiter to the last closed flux surface (LCFS) was from 4 to 8.5 cm. The parameters of the shots discussed in this paper are given in table 1.

The magnetic field lines connect to the divertor region after N toroidal turns. The connection length is then given roughly by $L = 2\pi R_0 N$, where R_0 is the major radius. For example, for shot 55761 from the first set the connection takes place after $N = 3.5$ turns. Consequently, the connection length is about 65 m at the time this shot shows hot spots.

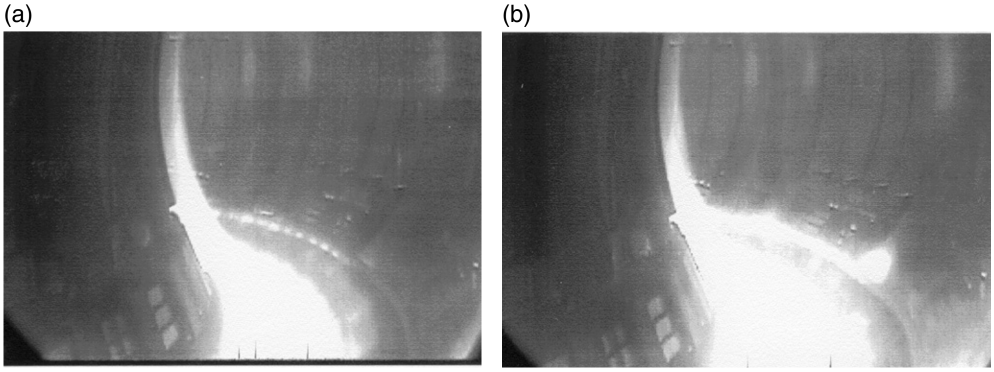

Figure 2. Hot spots on the outer divertor apron in shot 37338 seen by the CCD camera: LH power $P_{LH} = 2.5$ MW, gas rate near the grill $F_{GIM6} = 5.3 \times 10^{21}$ el s^{-1} (*a*) $t = 63.56$ s, $R_{grill} - R_{pol.Lim.} = 0$ cm (*b*) $t = 65.28$, $R_{grill} - R_{pol.Lim.} = 2$ cm.

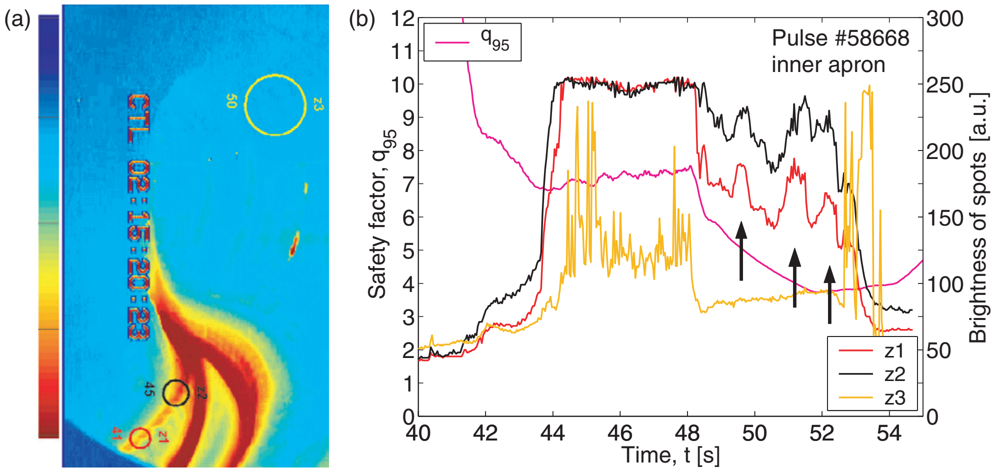

Figure 3. The left-hand side image shows the measuring points in the IRMA analysis, which is shown on the right-hand side for shot 58668. The right-hand side image also shows the safety factor versus time. During the first phase of the pulse, from $t = 44$ to 48 s, the brightness is higher because of the ELMy phase.

3. Hot spots on divertor aprons

Hot spots at JET were observed for the first time in 1996. Reference [10] shows very clear spots on the outer divertor apron in shot 37338. The spots at two different times are shown in figure 2. At the time of the spots, the q_{95}-value was very low, i.e. $q_{95} = 3.1$. It is interesting to note that the hot spots are much brighter in the figure to the right, when the grill is retracted 2 cm behind the limiter. In this case, all the rows below the mid-plane were connected to the divertor apron, which would explain the stronger brightness, whereas only a few rows were connected when the grill was flush with the limiter [10].

In the shots of the new work presented here, evident chains of bright spots were seen on the inner divertor apron. The chains can be seen in figure 3(*a*). These spots move toroidally round the torus as the q-value changes and, therefore, we call them 'trains'. These bright spots are clearly marks of the effect of magnetic connection between the divertor apron and the grill. According to field line tracing calculations, the field lines starting in front of the grill limiter do not hit any in-vessel components before ending up on the divertor apron. The toroidal extent of the trains is consistent with the poloidal height of the grill. The absolute location is not completely right, which is not surprising as the error per turn is quite large and the field lines make from 3.5 to 5 turns in each shot. Moreover, at the time between the observed bright spots the field lines end up on the divertor about half a turn away from the location when the spots are seen. However, the toroidal motion obtained from the series of field line tracing calculations is consistent with the rotational transform seen by the CCD camera. For low enough q_{95}, the connection can also be seen on the outer divertor apron after less than one turn. In this case, the field line tracing calculations show the connection of the bright spots to the LH grill mouth with sufficient accuracy.

The CCD videos of the pulses showing bright spots were analysed with the IRMA (Infra Red Movie Analyser) software [11], which evaluates the brightness in the CCD camera pictures. Two or three measuring points were used on the apron and one on the wall in order to obtain the background brightness. The analysis gives a time dependence of the brightness showing for the third set clear increases at the measuring points in the current ramp-up phase of the discharges. For shot 58668 of the third set, the measuring points are shown in figure 3 together with the result of the IRMA analysis. The first part of the pulse from $t = 44$ to 48 s was dedicated to the long distance coupling in ITER relevant conditions, i.e. an ELMy H-mode scenario with large plasma–wall distance. Because of the high brightness due to ELMs, the possible increase due to the LH power generated spots cannot be distinguished from the figures. The brightness shows three clear peaks in the second phase of the shot starting at $t = 48$ s. The arrows in figure 3 denote the peaks for shot 58668. The figure also presents the q_{95}-value. The two earlier pulses 58666 and 58667 show a structure similar to this one. In each of these three shots, the q_{95} windows at which peaks are observed, are roughly the same. The first window is $q_{95} = 5.1$–4.5 just before $t = 50$ s. The second peak is at about $t = 51.1$–51.9 s with $q_{95} = 4.1$–3.8 and the last one is around $q_{95} = 3.8$ starting at $t = 52.3$. The last peak ends at about $t = 52.5$ s at the switch-off of the 3 MW lower hybrid power. The connection lines end up on the divertor exactly at the same toroidal position, for the two later peaks just after one turn less than for the first peak. The two other sets showed bright spots in the CCD videos also at lower q_{95} values, i.e. at $q_{95} = 3.4$ and $q_{95} = 3.13$, which could not be reached in the third set. The q_{95}-windows for the shots of this work are summarized in table 1. The brightness in the pulses analysed in this work was much lower than the one in the old shots, perhaps also because of the much shorter connection length for the old shots. In addition, the particles were hitting the poloidal limiter in the old shots. Because of a large impact angle, the brightness was much higher at that location. The divertor configuration has also been changed since the old shots, and therefore the recycling conditions may be different. Finally, the magnetic configuration was not the same. In shot 37338, shown in figure 2, the brightness of the spots was about twice the background brightness, while in these shots the brightness only increased by about 10%.

Just before the switching off of the LH power, the brightness also increased on the outer apron in these three shots of the third set. However, this increase was much smaller than on the inner apron and was only discovered by the IRMA software. Unfortunately, the lowest q-value that could be obtained was restricted and the spots did not reach far into the visual field of the CCD camera.

The dependence of the spots on various parameters was then analysed. The brightness was ranked on a scale from 0 to 5. No dependence on ion cyclotron resonance heating (ICRH) or neutral beam injection (NBI) power was observed. However, we did not distinguish between

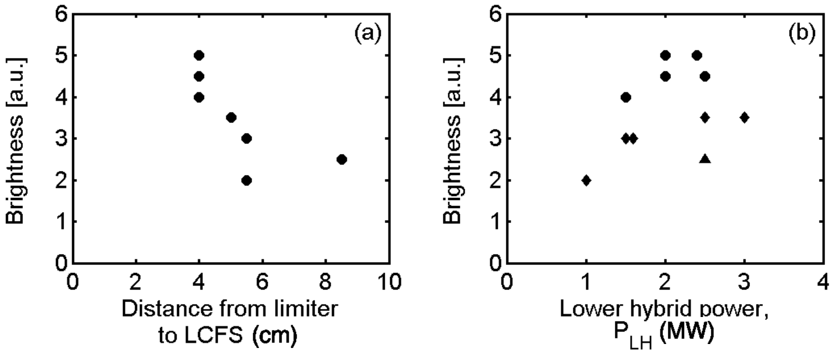

Figure 4. Brightness of the hot spots in the inner divertor apron obtained from the CCD camera versus (*a*) the distance from the limiter to the last closed flux surface (LCFS) and (b) the LH power. The different symbols denote different plasma–grill distances: bullet 5.5 cm, diamond 6.5 cm and triangle 10.5 cm. The parameters of these shots are given in table 1.

the possible effect from the four ICRH antennae located at different toroidal locations [12]. The ICRH power varied from 3 to 5 MW and the NBI power from 6 to 15 MW. The brightest spots were obtained when the grill was 15 mm behind the limiter, but the position with respect to the limiter did not have a strong effect. This might be due to the assumption that the fast particle beam is created at a certain radial distance from the grill. Langmuir probe measurements of the fast particle beam have been carried out in front of the grill of the small CASTOR tokamak [13]. In those measurements, the dip of the floating potential indicating the maximum intensity of the fast particle beam was radially several millimetres from the grill mouth. This suggests that the fast particle beam is formed slightly further outside the grill mouth.

The most important parameter seems to be the distance from the limiter to the last closed flux surface. The brightness decreases with increasing distance, as can be seen in figure 4(*a*). The figure shows the brightness of the spots versus the distance from the limiter to the last closed flux surface. This is beneficial for ITER as it is designed to have a large plasma–wall distance. The LH coupling in ITER relevant JET configurations has been demonstrated and is discussed in more detail in [1, 14]. The dependence of the brightness on the coupled LH power is shown in figure 4(*b*) in which an increase in the brightness with the power can be seen. This is in accordance with observations made at Tore Supra and TdeV [3, 4] as well as theoretical analysis [6], both of which show an increase in the heat flux with LH power. A stronger magnetic field seems to increase the brightness of the spots slightly. This may be because the particles are better confined around the magnetic field lines since the Larmor radius is smaller at a larger field. Consequently, the particles deposit their energy on a smaller area on the wall.

The lower edge density in front of the launcher could be a reason for the observed decrease in the brightness with increasing plasma–wall distance. However, the coupling was very good in the analysed pulses due to gas puffing close to the grill. Moreover, the density dependence of the coupling is very weak for densities exceeding 2 to 3 times the cut-off density. The propagation of the particle beam further away from the grill could also be affected by non-linear effects due to the lower density there. The interaction point is changed and further out on the apron the beam hits less recycling surfaces. Consequently, the brightness is lower for the same heat flux.

Finally, the study did not show a clear dependence on the reflection coefficient R. However, frequent tripping of the LH power due to problems with LH wave coupling was observed during these experiments. We note in this connection that the reflection coefficient as well as the plasma density in front of the LH grill may also vary with the LH power, as observed in Tore Supra. Theoretical analysis shows that such variations in the reflection coefficient and plasma density can result from the charge separation fields produced by the parasitic electron acceleration [15, 16].

4. Summary

Bright spots have been observed at JET and they are similar in nature to those observed at Tore Supra and TdeV [3, 4]. These spots are formed due to parasitic absorption of the short wavelength modes of the wave spectrum, which create beams of fast particles in front of the grill. The results presented in this paper are in good agreement with this theory. The brightness is clearly related to the lower hybrid power as the spots disappear when the LH power is turned off. Moreover, the toroidal rotation of the spots is consistent with the movement of the connection point of the field lines on the divertor apron obtained from a field line tracing calculation. This allows the conclusion that the fast particles that are created within a thin layer in front of the grill can rotate several times around the torus before ending up on the wall, similarly as at Tore Supra [3].

The spots were studied visually from the CCD videos. Their brightness was further analysed with the IRMA software. The study showed that the brightness indeed increases on the divertor apron when LH power is applied. The brightness of the spots varied as shown in figure 4. On the outer apron, the IRMA analysis also revealed bright spots that were not detected in the CCD videos by the naked eye.

The brightness of the spots was analysed as a function of various parameters. The LH power clearly causes the bright spots. The most important parameter, however, seemed to be the plasma–wall distance, i.e. the distance from the last closed flux surface to the limiter. The brightness of the spots clearly decreased with increasing distance. This is very favourable for ITER, which is designed to operate at a large plasma–wall distance. The dependence on other parameters was either weak or ambiguous.

Acknowledgments

Part of the work was supported through the Czech grant projects GA AV 1043101 and GACR 202/04/0360.

References

[1] Ekedahl A *et al* 2003 *Proc. 15th Topical Conf. on Radio Frequency Power in Plasmas (Moran, Wyoming, USA, 19–21 May 2003)* (New York: AIP) vol 694 pp 227–34

[2] Rantamäki K M *et al* 2003 *30th EPS Conf. on Controlled Fusion and Plasma Physics (St Petersburg, Russia, 7–11 July 2003)* vol 27A (European Conference Abstracts) P-1.190

[3] Goniche M *et al* 1998 *Nucl. Fusion* **28** 919

[4] Mailloux J *et al* 1997 *J. Nucl. Mater.* **241–243** 745

[5] Fuchs V, Goniche M, Demers Y, Jacquet P and Mailloux J 1996 *Phys. Plasmas* **3** 4023–35

[6] Rantamäki K M, Pättikangas T J H, Karttunen S J, Bibet P, Litaudon X and Moreau D 2000 *Nucl. Fusion* **40** 1477

[7] Moreau D, Gormezano C, Meling G and Nguyen T K 1984 *Radiation in Plasmas* vol 1, ed B McNamara (Singapore: World Scientific) p 331

[8] Rantamäki K M, Pättikangas T J H, Karttunen S J, Litaudon X, Moreau D, Bibet P and Ekedahl A 1999 *Plasma Phys. Control. Fusion* **41** 1125–33

[9] Coad J P, Lingertat J, Migozzi J-B, Stott P E, Walker C I and Wilson C H 1997 *24th EPS Conf. (Berchtesgaden, Germany, 9–13 June 1997)* vol 21A (European Conference Abstracts) (part I) p 145

[10] Goniche M, Dobbing J A, Ekedahl A, Schild P and Söldner F X 1997 *JET Report JET-R(97)14* http://www.iop.org/ Jet/fulltext/JETR97014.pdf

[11] Person S 1997 Infra Red Movies Analysis IRMA2, Tore Supra software, September 1997

[12] Ekedahl A *et al* 2003 *Proc. 15th Topical Conf. on Radio Frequency Power in Plasmas (Moran, Wyoming, USA, 19–21 May 2003)* (New York: AIP) vol 694, p 259

[13] Zacek F, Petrzilka V, Devynck P, Goniche M and Nanobashvili S 2003 *30th EPS Conf. on Controlled Fusion and Plasma Physics (St Petersburg, Russia, 7–11 July 2003)* vol 27A (European Conference Abstracts) P-1.196

[14] Granucci G *et al* 2003 *30th EPS Conf. on Controlled Fusion and Plasma Physics (St Petersburg, Russia, 7–11 July 2003)* vol 27A (European Conference Abstracts) P-1.191

[15] Petrzilka V, Ekedahl A, Fuchs V, Goniche M, Gunn J, Krlin L, Kuhn S, Rantamäki K, Tskhakaya D and Zacek F 2003 *30th EPS Conf. on Controlled Fusion and Plasma Physics (St Petersburg, Russia, 7–11 July 2003)* vol 27A (European Conference Abstracts) P-1.195

[16] Tskhakaya D *et al* 2002, Varenna 2002 *Fusion Theory Conference* p 209–22 (invited paper)